Design of the Superconducting RFQ for PIAVE Linac (NUCLEAR SCIENCE RESEARCH FACILITY?Particle and Photon Beams)

Simulation Study of Three-Dimensional Laser Cooling Method for Fast Stored Ion Beams

Takahiro Kihara, Hiromi Okamoto and Yoshihisa Iwashita

Three-dimensional (3D) laser cooling method of fast stored ion beams based on linear coupling mechanism is explored. We employ the tracking code "SAD", showing that resonant coupling remarkably enhances transverse cooling rates. Molecular dynamics (MD) code "SOLID" is also employed to study the effect of space charges and the possibility of beam crystallization.

Keywords : Beam-Cooling/ Coupling/ Simulation/ Space-Charge/ Storage Ring

To our current knowledge, Doppler laser cooling is the most promising technique in achieving the highest possible phase-space density of ion beams [1]. It has already been experimentally demonstrated that one can produce an ultra-cold beam close to the longitudinal space-charge limit [2, 3]. In contrast, laser cooling in the transverse directions has been much less effective. Therefore one may need to develop some novel approach in order to extend the powerful laser cooling force to the transverse degrees of freedom.

For this purpose, a novel method has been proposed in the previous publications [4, 5]. The idea is simple, that is, we develop a synchrobetatron coupling to indirectly increase the transverse cooling rates. The coupling source theoretically considered was the linear potential induced either by *momentum dispersion* in a regular RF cavity [4], or by a special *coupling cavity* operating in TM_{210} mode [5]. It has been proven that the transverse cooling rates can be most enhanced under the resonance conditions

$$\nu_s - \nu_x \approx \text{integer} \quad \text{and} \quad \nu_x - \nu_y \approx \text{integer}, \qquad (1)$$

where ν_x, ν_y, and ν_s are, respectively, the horizontal, vertical and longitudinal tunes.

In order to carry out reliable numerical experiments where realistic lattice structures of storage rings is taken into account, we employed the tracking code "SAD (Strategic Accelerator Design)" [6] to systematically explore the behavior of the beam at high temperature. As an example, we considered the lattice parameter of the ASTRID ring in Denmark [2], one of the two storage rings in which a laser cooling system has been installed (another is the TSR ring in Germany [3]). Under the typical operating condition of ASTRID, we obtain Fig. 1(a), where no transverse cooling is visible. On the other hand, Fig. 1(b) corresponds to the case where the lattice parameters have been modified so as to roughly satisfy the resonance conditions in Eq. (1). The effectiveness of the coupling scheme is evident.

The effect of particle Coulomb interactions dominates

NUCLEAR SCIENCE RESEARCH FACILITY — Beams and Fundamental Reaction —

Scope of research

Particle beams, accelerators and their applications are studied. Structure and reactions of fundamental substances are investigated through the interactions between beams and materials such as nuclear scattering. Tunable lasers are also applied to investigate the structure of unstable nuclei far from stability and to search for as yet unknown cosmological dark-matter particles in the Universe.

Prof
INOUE, Makoto
(D Sc)

Assoc Prof
MATSUKI, Seishi
(D Sc)

Instr
OKAMOTO, Hiromi
(D Sc)

Students
KAPIN, Valeri (RF)
TADA, Masaru (DC)
KISHIMOTO, Yasuhiro (DC)
AO, Hiroyuki (DC)
SHIBATA, Masahiro (MC)
OOISHI, Chikara (MC)

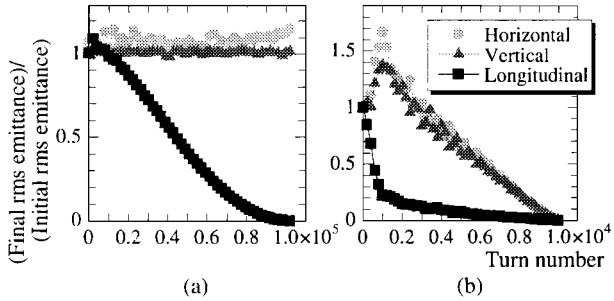

Figure 1. SAD simulation results. The time evolutions of root-mean-squared (rms) beam emittances are plotted. The case (a) corresponds to the ordinary operating mode of ASTRID while the lattice parameters have been modified in the case (b) such that the resonance conditions in Eq. (1) are satisfied.

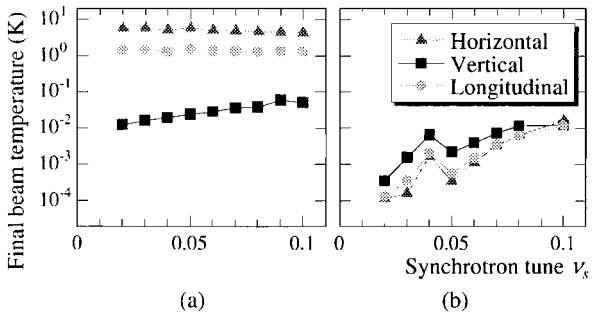

Figure 2. Equilibrium beam temperatures vs. operating synchrotron tune, obtained from SOLID. In the case (a), the same resonant ASTRID lattice as employed in Fig. 1(b) has been considered, while the case (b) corresponds to the modified TARN II lattice where the resonance conditions Eq. (1) are satisfied.

the beam at low temperature. Thus we need to examine the effect of space charges on the final temperature, employing the MD code "SOLID" [7]. Figure 2(a) illustrates the ν_s-dependence of the final beam temperature in the resonant ASTRID lattice. It is shown that the coupling method achieved transverse temperatures of the order of 1K. Beam crystallization is, however, still not achievable in this temperature region.

The lattice of a storage ring suitable for beam crystallization must fulfill the so-called maintenance condition given by [8]

$$\max(\nu_x,\nu_y) < N_l/2\sqrt{2} \qquad (2)$$

where N_l is the lattice superperiodicity. Since ASTRID does not satisfy this necessary condition of beam crystallization, we now consider, among a wide range of choice, the lattice parameters of the storage ring TARN II [9]. The beam temperatures achieved in TARN II by means of the coupling method are plotted in Fig. 2(b). We see that the transverse temperatures have now become more than two orders of magnitude lower than those in the ASTRID case. Figure 3 displays the real-space profile of an equilibrium beam laser-cooled in TARN II. As anticipated, we see a 3D ordered structure formed.

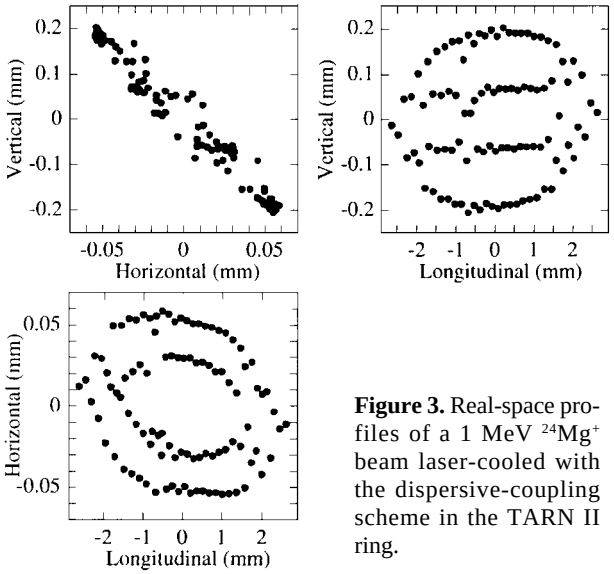

Figure 3. Real-space profiles of a 1 MeV $^{24}Mg^{+}$ beam laser-cooled with the dispersive-coupling scheme in the TARN II ring.

To summarise, we have studied the fundamental properties of the 3D laser cooling methods based on linear synchrobetatron coupling. It has been clearly demonstrated that the transverse cooling time can remarkably be shortened by using the coupling schemes. Provided that the lattice parameters of a ring satisfy the maintenance condition, equilibrium transverse temperature well below 1K could be reached very quickly, and beam crystallization is realized.

The MD simulation program was originally developed by Dr. X.-P. Li and J. Wei. Computation time was partially provided by the SAD cluster of KEK, and the Super-computer Laboratory, Institute for Chemical Research, Kyoto University.

References

1. D. J. Wineland and H. Dehmelt, Bull. Am. Phys. Soc. 20 (1975) 637 ; T. Hansch and A. Schawlow, Opt. Commun. 13 (1975) 68.
2. J. S. Hangst at al., Phys. Rev. Lett. 67 (1991) 1238.
3. S. Schroder et al., Phys. Rev. Lett. 64 (1990) 2901.
4. H. Okamoto, A. M. Sessler and D. Mohl, Phys. Rev. Lett. 72 (1994) 3977.
5. H. Okamoto, Phys. Rev. E50 (1994) 4982.
6. For the details of the SAD code, see : http://www-acc-theory.kek.jp/SAD/sad.html
7. For the information of SOLID, see, e.g., J. Wei, X.-P. Li, and A. M. Sessler, BNL Report BNL-52381 (1993).
8. See, e.g., J. Wei, A. Draeseke, A. M. Sessler, and X.-P. Li, Crystalline Beams and Related Issues (World Scientific Publishing Co. Pte. Ltd., Singapore, 1996) p. 229.
9. T. Katayama et al., in Proceedings of the 2nd European Particle Accelerator Conference, 1990, (Nice, 1990), p. 577.